Fermi-Liquid Behavior of the Low-Density 2D Hole Gas in a GaAs/AlGaAs Heterostructure at Large Values of r_s

Y. Y. Proskuryakov,[1] A. K. Savchenko,[1] S. S. Safonov,[1] M. Pepper,[2] M. Y. Simmons,[2] and D. A. Ritchie[2]

[1]*School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom*
[2]*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, United Kingdom*

(Received 12 January 2001)

We examine the validity of the Fermi-liquid description of the dilute 2D hole gas in the crossover from "metallic"-to-"insulating" behavior of $\rho(T)$. It has been established that, at r_s as large as 29, negative magnetoresistance does exist and is well described by weak localization theory. The dephasing time, extracted from the magnetoresistance, is dominated by the T^2 term due to hole-hole scattering in the clean limit. The effect of hole-hole interactions, however, is suppressed when compared with the theory derived for small r_s.

DOI: 10.1103/PhysRevLett.86.4895 PACS numbers: 73.40.Qv, 71.30.+h, 73.20.Fz

There has recently been much attention drawn to the unusual crossover in the temperature dependence of resistivity with varying carrier concentration from "metallic" ($d\rho/dT > 0$) to "insulating" ($d\rho/dT < 0$) behavior seen in some clean low-density 2D systems [1]. With decreasing carrier density p the ratio of the Coulomb to Fermi energy $r_s = U/E_F \propto m^*/p^{1/2}$ increases, so it was suggested that the Fermi-liquid approach is not valid for the description of these systems and the crossover is a manifestation of a critical metal-to-insulator transition [2]. In [3] the insulating state at a low hole density of $p \simeq 7.7 \times 10^9$ cm^{-2} and interaction parameter $r_s \simeq 35$ ($m^* = 0.37\ m_0$) was attributed to Wigner crystallization expected at such large r_s [4]. On the other hand, there were views that the crossover is caused by a nontrivial behavior of conventional charge carriers [5]. In this work we study the magnetoresistance of a low-density 2D hole gas in the crossover region and examine its description in terms of the effects of weak localization (WL) and weak hole-hole interaction (HHI). Since the theories of WL and HHI are derived for $r_s \ll 1$ [6,7], they provide a good test for a conventional Fermi liquid. In particular, important information about interacting particles can be obtained from the dephasing rate which controls the WL effect.

There have already been indications that the 2D hole gas behaves as a Fermi liquid at $r_s \sim 10$–14, as far as WL and HHI are concerned [8,9]. One can argue though that in those structures the mobility was not high enough, and carrier density not low enough for the deviations from the Fermi liquid to be seen (in [8] the 2D hole gas had peak mobility $\mu_p = 2.5 \times 10^5$ cm^2 V^{-1} s^{-1} and carrier density down to $p \simeq 4.6 \times 10^{10}$ cm^{-2}). We study structures with higher mobility and lower density ($\mu_p = 6.5 \times 10^5$ cm^2 V^{-1} s^{-1} and $p = 1.17 \times 10^{10}$ cm^{-2}) which approach in quality those in [3] where the Wigner crystal formation has been claimed. Surprisingly, our results show that at r_s as large as 29 the strong Coulomb interaction does not affect the WL description of the negative magnetoresistance [10,11], although it suppresses the contribution of HHI both to the phase-breaking time and the Hall coefficient.

The experiments have been performed on a heterostructure formed on a (311)A GaAs substrate, where the 2D hole gas at the GaAs/AlGaAs interface is separated from the Si-modulation doped layer by a 500 Å AlGaAs spacer. A standard four-terminal low-frequency lock-in technique has been used for resistivity measurements at temperatures down to 45 mK, with currents of 1–10 nA to avoid electron heating. The hole density p is varied by the front gate voltage in the range of r_s from 10 to 29 (with effective mass m^* taken as 0.38 m_0 [12]).

Figure 1a shows a typical temperature dependence of the longitudinal resistivity in our samples. The low part of the plot (high hole densities) has a metallic behavior with $d\rho/dT > 0$. As the density is decreased, $\rho(T)$ becomes nonmonotonic and further decreasing p leads to an insulating dependence with $d\rho/dT < 0$. In the metal to insulator

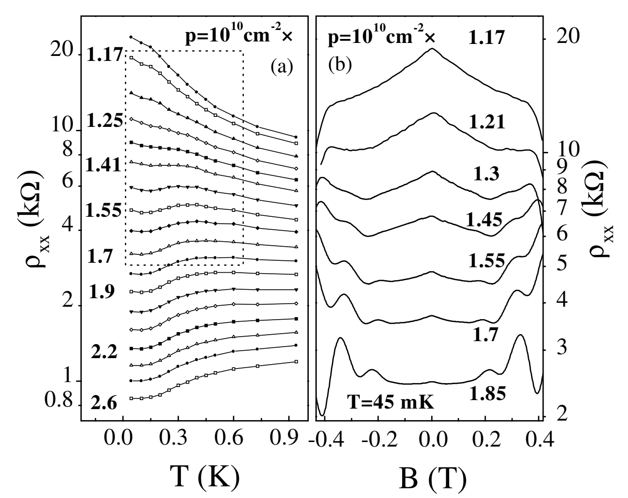

FIG. 1. (a) Temperature dependence of the resistivity at different hole densities. The dashed box encloses the domain of the negative magnetoresistance (NMR) study. (b) NMR at $T = 45$ mK, for different hole densities.

crossover, where r_s varies from 23 to 29, we have observed negative perpendicular magnetoresistance, Fig. 1b, which increases with lowering the hole density. [The density for a given gate voltage V_g has been determined from the Shubnikov–de Haas (SdH) oscilllations.]

It is natural to ascribe this effect to WL which occurs due to quantum interference of elastically scattered carriers on closed phase-coherent paths. Great care, however, should be taken in analyzing WL in the magnetoresistance of high-mobility structures. First, the application of the conventional WL theory, based on the diffusion approximations, is restricted by the range of magnetic fields $B < B_{\rm tr}$, where $B_{\rm tr} = \hbar/4De\tau$ is the "transport" magnetic field, D is the diffusion coefficient, and τ is the momentum relaxation time [7]. Physically, this means that the magnetic length L_B has to be larger than the mean free path l, so no negative magnetoresistance is expected in this approach for $B > B_{\rm tr}$. In our high mobility samples the value of $B_{\rm tr}$ is very small, ranging from 0.003 to 0.08 T for the densities studied. At the same time, the NMR is observed up to $B \sim 0.2$ T where SdH oscillations start. This means that even at $B > B_{\rm tr}$ there is a phase-breaking effect of magnetic field acting on the trajectories smaller than L_B (and smaller than l). The theory of WL in such a regime has been considered in several papers [10,11], although no experimental tests of the theories have yet been performed. Second, the theories of WL discuss the positive magnetoconductivity $\Delta\sigma^{\rm WL}(B) = \delta\sigma_{xx}(T,B) - \delta\sigma_{xx}(T,0)$, which is due to the decrease of the quantum (negative) correction $\delta\sigma_{xx}(T,B)$ to the classical (Drude) conductivity. The phase-breaking effect of magnetic field is usually seen at small fields, where, in low-mobility structures, the magnetic field effect on the Drude conductivity is negligible. To analyze $\Delta\sigma^{\rm WL}(B)$ in a high mobility system, one should take into account the magnetic field dependence of the Drude conductivity itself:

$$\sigma_{xx}^D(B) = \frac{\sigma_0}{1 + (\mu B)^2}\,. \tag{1}$$

Figure 2 shows the total conductivity as a function of magnetic field obtained by inversion of the resistivity tensor, $\sigma_{xx}^{\rm tot}(B) = (1/\rho_{xx})/(1 + \rho_{xy}^2/\rho_{xx}^2)$, where $\rho_{xx}(B)$ and $\rho_{xy}(B)$ are measured simultaneously. The dotted lines are plotted using the classical expression Eq. (1) with $\mu B = \rho_{xy}(B)\sigma_0$. The zero-field conductivity σ_0 is found as an adjustable parameter to make the best fit in the higher field region of $\sigma_{xx}^{\rm tot}(B)$, where WL is expected to be totally suppressed. The difference between the solid and dotted lines gives the WL correction $\delta\sigma_{xx}(T,B)$, from which the zero-field value $\delta\sigma_{xx}(T,0)$ is then subtracted to obtain the required dependence $\Delta\sigma^{\rm WL}(B)$.

For data analysis we use the WL theory [10] developed beyond the diffusion approximation. It gives the magnetoconductivity at an arbitrary ratio $B/B_{\rm tr}$, provided $\tau < \tau_\varphi$ is satisfied:

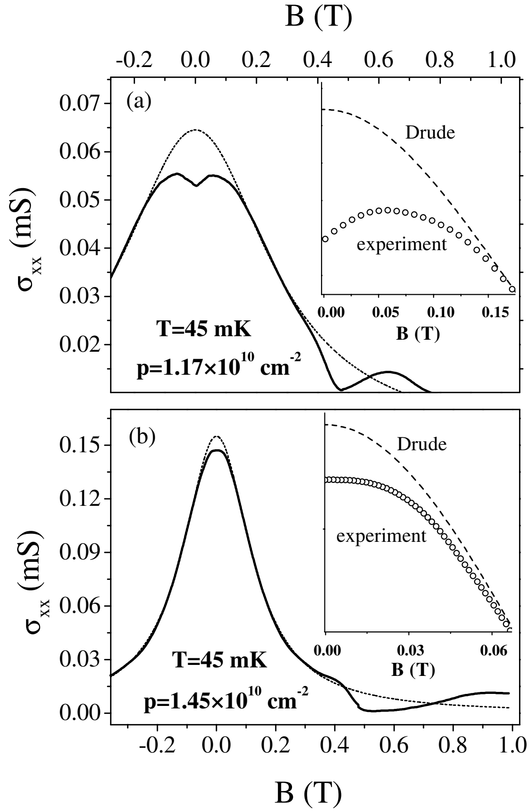

FIG. 2. (a,b) Experimental (total) conductivity $\sigma_{xx}(B)$ shown by solid lines in the figures and circles in the insets (the insets present zoomed-in regions). Dashed lines in the insets represent the classical magnetoconductivity Eq. (1).

$$\Delta\sigma^{\rm WL}(B) = \frac{-e^2}{\pi h(1+\gamma)^2} \times \left[\sum_{n=0}^{N}\left(\frac{b\cdot\psi_n^3(b)}{1+\gamma-\psi_n(b)}\right) - \ln\frac{1+\gamma}{\gamma}\right], \tag{2}$$

where $\gamma = \tau/\tau_\varphi$, τ_φ is the dephasing time, $b = \frac{1}{(1+\gamma)^2}\frac{B}{B_{\rm tr}}$, $\psi_n(b) = \int_0^\infty d\xi\, e^{-\xi - b\xi^2/4}L_n(b\xi^2/2)$, and L_n are the Laguerre polynomials. In Fig. 3a we show representative data at different densities in the middle of the studied temperature range, plotted against dimensionless magnetic field $B/B_{\rm tr}$, with $B_{\rm tr}$ found as $(4\pi\hbar\mu\sigma_0/e^2)^{-1}$. Solid lines in Fig. 3 are obtained from Eq. (2), where γ is used as an adjustable parameter. The obtained γ values range from 0.04 to 0.4 and satisfy the condition $\tau < \tau_\varphi$. The accuracy of γ is not strongly affected by the error in determining the value σ_0, Fig. 2. [This is primarily due to the fact that $\Delta\sigma^{\rm WL}(B)$ in Eq. (2) is plotted as a function of the dimensionless field which is also dependent on σ_0.] The error in σ_0 varies from 4% at lowest densities to 0.2% at highest densities. The error in the WL correction $\Delta\sigma^{\rm WL}$ becomes then 20 and 5%, respectively. These values correspond to the lowest temperature, and they decrease by a factor of 10–100 with increasing temperature. It is important that in all cases the error in determining the value of γ does not exceed 10%.

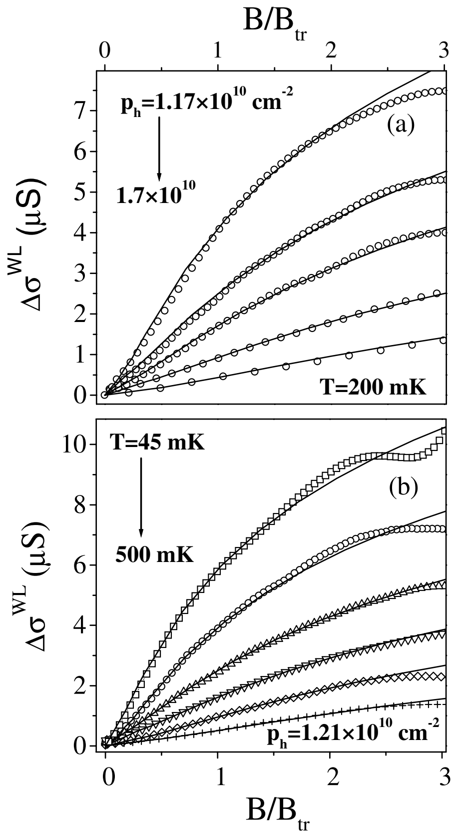

FIG. 3. Magnetoconductivity $\Delta\sigma_{xx}^{\mathrm{WL}}$ as a function of dimensionless magnetic field ($B_{\mathrm{tr}} = \hbar/4De\tau$). (a) $p = 1.17$, 1.21, 1.3, 1.45, 1.7×10^{10} cm^{-2} at $T = 200$ mK; (b) $p = 1.21 \times 10^{10}$ cm^{-2} at $T = 45$, 120, 200, 300, 400, 500 mK. Solid lines are fit to Eq. (2).

The apparent agreement with WL theory suggests that, surprisingly, even at $r_s \sim 23-29$ the Fermi-liquid description of the system remains valid. The further evidence for this has been obtained from analysis of the temperature dependence of the dephasing rate $\tau_\varphi^{-1}(T)$. Estimations show that the contribution to $\tau_\varphi^{-1}(T)$ from electron-phonon scattering [13] is negligible in the studied temperature range. According to the Fermi-liquid theory [6,14,15], the dephasing rate due to electron-electron scattering is dominated either by a linear or quadratic term, dependent on the parameter $k_B T\tau/\hbar$:

$$\tau_\varphi^{-1}(T) = \alpha \frac{(k_B T)^2}{\hbar E_F} \ln\left(\frac{4E_F}{k_B T}\right), \qquad \text{when } k_B T\tau/\hbar \gg 1, \tag{3}$$

$$\tau_\varphi^{-1}(T) = \frac{k_B T}{2E_F\tau} \ln\left(\frac{2E_F\tau}{\hbar}\right), \quad \text{when } k_B T\tau/\hbar \ll 1, \tag{4}$$

where $\alpha = \pi/8$ [15]. The quadratic term in Eq. (3) is due to Landau-Baber scattering associated with collisions with large momentum transfer in a clean Fermi liquid, and the linear term in Eq. (4) corresponds to particle-particle interactions with small energy transfer in a disordered conductor. In the experiment, the parameter $k_B T\tau/\hbar$ varies with temperature from 0.06 to 0.8 for the lowest density and from 0.1 to 0.9 for the highest density, so that we need to examine the applicability of both expressions to the dependence $\tau_\varphi^{-1}(T)$ extracted from the analysis of the magnetoresistance data, Fig. 4a.

In the studied sample a shift of the Shubnikov–de Haas minima was seen with increasing temperature, indicating a weak (~10%) increase of the hole density. Thus, it was convenient to analyze the dephasing rate as the product $\tau_\varphi^{-1}p$, with density p directly measured at each temperature by the SdH effect. In this case Eqs. (3) and (4) are rewritten, respectively, as

$$\tau_\varphi^{-1}p = \frac{m^*}{\pi\hbar^3}\left[\alpha k_B^2 T^2 \ln\left(\frac{4E_F}{k_B T}\right)\right], \tag{5}$$

$$\tau_\varphi^{-1}p = \frac{m^*}{\pi\hbar^3}\left[k_B T \frac{\hbar}{2\tau} \ln\left(\frac{2E_F\tau}{\hbar}\right)\right]. \tag{6}$$

The experimental curves in Fig. 4a show two distinct features: a nonlinear form, and a saturation at low

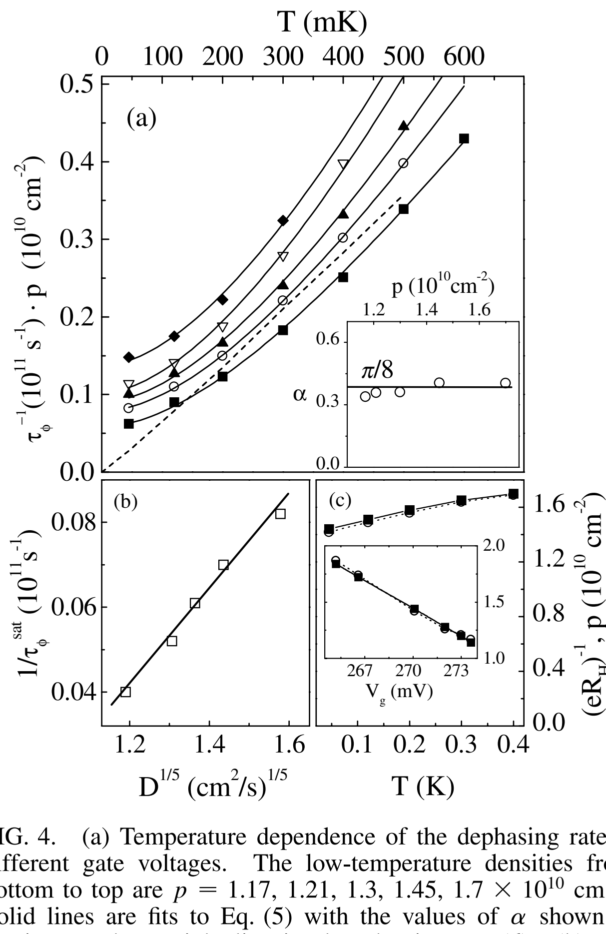

FIG. 4. (a) Temperature dependence of the dephasing rate at different gate voltages. The low-temperature densities from bottom to top are $p = 1.17$, 1.21, 1.3, 1.45, 1.7×10^{10} cm^{-2}. Solid lines are fits to Eq. (5) with the values of α shown in the inset. The straight line is plotted using Eq. (6). (b) The saturation value of the dephasing rate at $T = 0$ against diffusion coefficient. (c) The Hall coefficient at different temperatures, presented as $(eR_H)^{-1}$ (solid squares) for $p = 1.45 \times 10^{10}$ cm^{-2} at $T = 45$ mK. The density determined from the Shubnikov–de Haas effect is shown by open circles. Inset: Hole density measured by the Hall and SdH effects at different V_g, $T = 45$ mK.

temperatures. We have established that in the entire range of hole densities and temperatures, the data are well described by the quadratic term, Eq. (5), with a zero-temperature saturation value $1/\tau_\varphi(T=0) = 1/\tau_\varphi^{\mathrm{sat}}$ added to it. In the analysis of $\tau_\varphi(T)$ we used values p, E_F, and τ experimentally determined at each temperature. Coefficient α, found as an adjustable parameter, agrees within 20% accuracy with the value $\pi/8$ for all hole densities, inset to Fig. 4a. At the same time, the data show that the linear term in the dephasing rate is suppressed by more than an order of magnitude compared with the value estimated using Eq. (6). The expected contribution to the dephasing rate at a middle-range density $p = 1.3 \times 10^{10}$ cm^{-2} is shown in Fig. 4a as a dotted line.

In a conventional Fermi liquid, WL is usually accompanied by the HHI effect, which is seen as a quantum correction to both the conductivity and Hall coefficient. At small r_s, the two corrections are related as $\delta R_H(T)/R_H = -2\delta\sigma(T)/\sigma$ [6]. In [8] it was argued that in p-GaAs heterostructures HHI effect persists up to $r_s \sim 10$–14. We have now measured the temperature dependence of the Hall coefficient at much larger r_s. In Fig. 4c the Hall coefficient is presented as $(R_H e)^{-1}$ for different temperatures (solid squares). The decrease of R_H with increasing T appears to be of the right order of magnitude as estimated from theory for small r_s [6]. However, comparison with the hole density measured by the SdH effect has shown that the behavior of $(R_H e)^{-1}$ agrees, within 2%, with the temperature dependence of the density seen in this particular experiment. Also, the inset in Fig. 4c shows good agreement between the densities measured by Hall and SdH effects at different V_g. We suggest that the suppression of the temperature dependence $\delta R_H(T)$ is linked to the observed absence of the linear term in the dephasing rate.

Let us briefly discuss the saturation of τ_φ^{-1}. The problem of saturation of the dephasing rate at low temperatures has been known for many years [16,17], with several explanations suggested. In our case, the effect has one characteristic feature—the saturation becomes more pronounced with increasing hole density. This qualitatively agrees with the suggestion that its origin can be related to nonequilibrium external noise acting as an additional dephasing factor [16]. In this case, according to [16], the expected saturation is $1/\tau_\varphi^{\mathrm{sat}} \simeq D^{1/5}(\Omega e E_{\mathrm{ac}})^{2/5}$, where Ω is the radiation frequency and E_{ac} is the amplitude of an external ac field. In Fig. 4b the value $1/\tau_\varphi^{\mathrm{sat}}$ shows agreement with the $D^{1/5}$ dependence.

To summarize, we have found that the negative magnetoresistance of a high-mobility low-density 2D hole gas in the region of the crossover from "metal" to "insulator" is well explained by weak localization—in spite of large values of the interaction parameter $r_s \sim 23$–29. The applicability of the Fermi-liquid description to the crossover has been clearly seen in the dephasing rate $\tau_\varphi^{-1}(T)$. It has been found that it is dominated by Landau-Baber hole-hole scattering, which is an intrinsic property of a Fermi liquid in the clean limit. Further evidence of the Fermi-liquid character of the crossover comes merely from the fact that Shubnikov–de Haas oscillations have been detected in the whole range of densities, including those with insulating $\rho(T)$. It follows from our results that the temperature dependence of the conductivity near the crossover is dominated by the behavior of the classical Drude conductivity $\sigma_0(T)$.

We would like to note that the observed applicability of weak localization theory to the magnetoresistance of a strongly interacting system is an unusual result and requires further elucidation. The suppression, in the strongly interacting Fermi liquid, of weak hole-hole interactions in the dephasing rate and the Hall coefficient also deserves further attention.

We are grateful to B. L. Altshuler and D. L. Maslov for stimulating discussions, Harry Clark for help with fabricating the samples, and the EPSRC and ORS funds for financial support.

[1] S. V. Kravchenko *et al.,* Phys. Rev. B **50**, 8039 (1994); M. Y. Simmons *et al.,* Phys. Rev. Lett. **80**, 1292 (1998); Y. Hanein *et al.,* Phys. Rev. Lett. **80**, 1288 (1998); P. T. Coleridge *et al.,* Phys. Rev. B **56**, R12 764 (1997); A. P. Mills *et al.,* Phys. Rev. Lett. **83**, 2805 (1999).

[2] V. Dobrosavljevic *et al.,* Phys. Rev. Lett. **79**, 455 (1997); S. He and X. C. Xie, Phys. Rev. Lett. **80**, 3324 (1998); Q. Si and C. M. Varma, Phys. Rev. Lett. **81**, 4951 (1998).

[3] J. Yoon *et al.,* Phys. Rev. Lett. **82**, 1744 (1999).

[4] B. Tanatar *et al.,* Phys. Rev. B **39**, 5005 (1989).

[5] S. Das Sarma, E. H. Hwang, Phys. Rev. Lett. **83**, 164 (1999); B. L. Altshuler and D. L. Maslov, Phys. Rev. Lett. **82**, 145 (1999); B. L. Altshuler, D. L. Maslov, and V. M. Pudalov, Phys. Status Solidi (b) **218**, 193 (2000); Y. Meir, Phys. Rev. Lett. **83**, 3506 (1999).

[6] B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interaction in Disordered Systems,* edited by A. L. Efros and M. Pollak (North-Holland, Amsterdam, 1985).

[7] S. Hikami *et al.,* Prog. Theor. Phys. **63**, 707 (1980).

[8] M. Y. Simmons *et al.,* Phys. Rev. Lett. **84**, 2489 (2000).

[9] V. Senz *et al.,* Phys. Rev. Lett. **85**, 4357 (2000).

[10] H.-P. Wittman and A. Schmid, J. Low Temp. Phys. **69**, 131 (1987).

[11] A. P. Dmitriev *et al.,* Phys. Rev. B **56**, 9910 (1997); M. I. Dyakonov, Solid State Commun. **92**, 711 (1994); V. M. Gasparyan and A. Yu. Zuzin, Sov. Phys. Solid State **27**, 999 (1985).

[12] K. Hirakawa *et al.,* Phys. Rev. B **47**, 4076 (1993); H. L. Stormer *et al.,* Phys. Rev. Lett. **51**, 126 (1983).

[13] V. Karpus, Semicond. Sci. Technol. **5**, 691 (1990).

[14] H. Fukuyama *et al.,* Phys. Rev. B **27**, 5976 (1983).

[15] M. Reizer and J. W. Wilkins, Phys. Rev. B **55**, R7363 (1997).

[16] I. L. Aleiner *et al.,* Wave Random Media **9**, 201 (1999); B. L. Altshuler *et al.,* Physica (Amsterdam) **3E**, 58 (1998).

[17] P. Mohanty *et al.,* Phys. Rev. Lett. **78**, 3366 (1997).